Mathematical Programs with Complementarity Constraints*

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February 28, 2003

1 Introduction

An exciting new application of nonlinear programming techniques is mathematical programs with complementarity constraints (MPCC),

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & c(x) \geq 0 \\ & 0 \leq x_1 \ \perp \ x_2 \geq 0, \end{array} \tag{1.1}$$

where $x = (x_0, x_1, x_2)$ and $\perp$ is the complementarity operator, which requires that either a component $x_{1i} = 0$ or the corresponding component $x_{2i} = 0$. It is straightforward to include equality constraints in (1.1). Problems of this type arise in many engineering and economic applications; see the survey [6], the monographs [12, 13], and the growing collections of test problems [9, 4].

One attractive way of solving (1.1) is to replace the complementarity condition by a set of nonlinear inequalities, such as $X_1 x_2 \leq 0$, and then solve the equivalent nonlinear program (NLP),

$$\begin{array}{ll} \text{minimize} & f(x) \\ \text{subject to} & c(x) \geq 0 \\ & x_1,\ x_2 \geq 0,\ X_1 x_2 \leq 0, \end{array} \tag{1.2}$$

where $X_1 = \text{diag}(x_1)$. Unfortunately, it has been shown [15] that (1.2) violates the Mangasarian-Fromovitz constraint qualification (MFCQ) at *any* feasible point. This failure of MFCQ implies that the multiplier set is unbounded, the central path fails to exist, the active constraint normals are linearly dependent, and linearizations of (1.2) can become inconsistent *arbitrarily close* to a solution. In addition, early numerical experience with this approach has been disappointing [2]. As a consequence, solving MPCCs via NLPs such as (1.2) has been commonly regarded as numerically unsafe.

The failure of MFCQ in (1.2) can be traced to the formulation of the complementarity constraint as $X_1 x_2 \leq 0$. Consequently, algorithmic approaches have focused on avoiding this formulation. Instead, researchers have developed special purpose algorithms for MPCCs, such as branch-and-bound methods [2], implicit nonsmooth approaches [13], piecewise SQP methods [12], and perturbation and penalization approaches [5] analyzed in [16]. All of these techniques, however, require significantly more work than a standard NLP approach to (1.2).

Recently, exciting new developments have demonstrated that the gloomy prognosis about the use of (1.2) may have been premature. Standard NLP solvers have been used to solve a large class of MPCCs, written as NLPs, reliably and efficiently. This short note surveys these novel developments and summarizes open questions and possible extensions of these ideas.

The remainder is organized as follows. The next section provides a summary of certain stationarity concepts for MPCCs and establishes an important relationship with the Karush-Kuhn-Tucker (KKT) conditions of (1.2). This relationship is pivotal in the success of NLP solvers. The development of two important classes of solvers, sequential quadratic programming (SQP) and interior-point methods (IPMs), is charted in the subsequent two sections. The note concludes by providing a brief description of open problems.

2 The NLP Revolution

The resurgence of interest in the analysis of NLP solvers applied to (1.2) is motivated by the success of SQP methods in particular. A simple but key observation of Scholtes is that strong sta-

*Preprint ANL/MCS-P1026-0203

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tionarity is equivalent to the KKT conditions of (1.2).

A point x^* is called *strongly stationary* if and only if there exist multipliers $\lambda \geq 0$, $\hat{\nu}_1$, and $\hat{\nu}_2$ such that

$$\begin{array}{r} \nabla f^* - \nabla {c^*}^T \lambda - \begin{pmatrix} 0 \\ \hat{\nu}_1 \\ \hat{\nu}_2 \end{pmatrix} = 0 \\ c(x^*) \geq 0 \\ x_1^*, x_2^* \geq 0 \\ x_{1j}^* = 0 \text{ or } x_{2j}^* = 0 \\ c_i^* \lambda_i = 0,\ x_{1j}^* \hat{\nu}_{1j} = 0,\ x_{2j}^* \hat{\nu}_{2j} = 0 \\ \hat{\nu}_{1j} \geq 0,\ \hat{\nu}_{2j} \geq 0, \text{ if } x_{1j}^* = x_{2j}^* = 0. \end{array} \quad (2.1)$$

These are the KKT conditions of the *relaxed NLP* [15], which contains no complementarity condition and is therefore well behaved.

The KKT conditions of (1.2) are similar to (2.1), and this similarity will be exploited. Formally, a point x^* is called is a KKT point of (1.2) if and only if there exist multipliers $\lambda \geq 0$, $\nu_1 \geq 0$, $\nu_2 \geq 0$, and $\xi \geq 0$, such that

$$\begin{array}{r} \nabla f^* - \nabla {c^*}^T \lambda - \begin{pmatrix} 0 \\ \nu_1 - X_2 \xi \\ \nu_2 - X_1 \xi \end{pmatrix} = 0 \\ c(x^*) \geq 0 \\ x_1^*, x_2^* \geq 0 \\ X_1^* x_2 \leq 0 \\ c_i(x)\lambda_i = 0,\ x_{1j}\nu_{1j} = 0,\ x_{2j}\nu_{2j} = 0. \end{array} \quad (2.2)$$

Note that complementarity between ξ and $X_1^* x_2 \leq 0$ follows trivially. Now observe that (2.1) and (2.2) are equivalent if we set

$$\hat{\nu}_1 = \nu_1 - X_2 \xi \quad (2.3)$$

$$\hat{\nu}_2 = \nu_2 - X_1 \xi. \quad (2.4)$$

Hence there exists a *minimal value* of ξ, namely,

$$\xi_i = \begin{cases} 0 & \text{if } x_{1i}^* = x_{2i}^* = 0 \\ \max\left(0, \dfrac{-\hat{\nu}_{1i}}{x_{2i}^*}\right) & \text{if } x_{2i}^* > 0 \\ \max\left(0, \dfrac{-\hat{\nu}_{2i}}{x_{1i}^*}\right) & \text{if } x_{1i}^* > 0, \end{cases} \quad (2.5)$$

from which it follows that the unboundedness of the multipliers of (1.2) has a very special structure: the multipliers form a ray.

The fact that the KKT conditions of (1.2) are equivalent to strong stationarity implies the existence of bounded multipliers. This can be exploited in the analysis of SQP methods and in the design of robust IPM methods for MPECs.

3 SQP Lead the Way

SQP methods have recently been shown to solve MPCCs reliably as NLPs, despite the common folklore that this approach is doomed. Over 150 problems were solved, and the SQP solver obtained *quadratic* convergence for all but two problems [7].

This success of SQP methods has motivated renewed interest in the theoretical properties of SQP methods. In [1] it is shown that an SQP method with *elastic mode* converges locally. The key idea is to consider a penalized version of (1.2). The penalty problem satisfies MFCQ; and near a strongly stationary point, a sufficiently large penalty parameter can be found, similar to (2.5). Convergence can thus be established by using standard techniques.

In [8] it is shown that SQP converges superlinearly near a strongly stationary point. The proof is divided into two parts. First, it is shown that if ${x_1^{(k)}}^T x_2^{(k)} = 0$ at some iteration k, then the SQP approximation of (1.2) about this point is equivalent to the SQP approximation of the relaxed NLP. Since the latter is a well behaved problem, superlinear convergence follows. The second part of the proof assumes that ${x_1^{(k)}}^T x_2^{(k)} > 0$, and it is shown that each QP basis remains bounded away from singularity. Again, convergence can be established by using standard techniques.

One undesirable assumption in [8] is that all QP approximations are consistent. This is trivially true if ${x_1^{(k)}}^T x_2^{(k)} = 0$ for some k, and it can be shown to hold if the lower-level problem satisfies a certain mixed-P property [12]. In practice [7], a simple heuristic is implemented that relaxes the linearization of the complementarity constraint.

4 Interior-Point Methods

In contrast to SQP methods, interior-point methods (IPMs) are not as robust at solving MPCCs. Using default settings, they solve about 80% of

MPCCs. This is still remarkable, however, considering that the constraint gradients are dependent and the central path fails to exist.

The reason for the nonexistence of the central path is the complementarity constraint. Clearly,

$$x_1 \geq 0 \,,\; x_2 \geq 0, \;\text{ and }\; X_1 x_2 \leq 0$$

have no interior. As a consequence, multipliers can become unbounded, resulting in slow progress (if any) toward the solution.

Three approaches to remedy this situation are being investigated. The first two are related to [16] and either relax the complementarity constraint or penalize it. The third approach mixes a simple active set heuristic with the IPM to identify and remove indices of bi-active constraints ($x_{1i} = 0 = x_{2i}$) [3]. It is not clear at present, however, what convergence properties this approach possesses.

The relaxation scheme [11, 14] introduces a parameter $\tau > 0$ and relaxes the complementarity constraint to

$$x_1 \geq 0 \,,\; x_2 \geq 0 \;\text{ and }\; X_1 x_2 \leq \tau.$$

A standard primal-dual method is then applied, and the parameter τ is controlled in conjunction with the barrier parameter. It can be shown that near a strongly stationary point, the multipliers remain bounded and the central path exists.

An alternative to relaxation is to introduce an ℓ_1 penalty for the complementarity constraint and add $\rho x_1^T x_2$ to the objective. The resulting penalized NLP satisfies MFCQ and is well behaved. In addition, since $x_1, x_2 \geq 0$, no absolute values are required, and the problem is smooth. Near a strongly stationary point, a sufficiently large (but finite) penalty parameter exists, and any IPM method converges to this stationary point. We are investigating techniques for updating the penalty parameter, ρ.

The two schemes can be shown to be equivalent in the sense that for every relaxation τ there exists a penalty parameter ρ such that both approaches give the same solution. We prefer to control the penalty parameter, however, as it allows us to control the multipliers directly.

Interior-point methods for MPCCs have also been considered in [12], for example, the penalty interior-point algorithm (PIPA). This is a hybrid SQP-IPM method that aims to remain interior *only* with respect to the variables in the complementarity constraint, by perturbing it to

$$x_1 \geq 0 \,,\; x_2 \geq 0, \;\text{ and }\; X_1 x_2 = \tau.$$

Note that the last constraint is an *equation*. It is possible to construct a simple example where $x_1^* = x_2^* = 0$ and the central path fails to exist. Thus, this perturbation is suitable only for problems without bi-active constraints. In [10] another example is constructed that shows that PIPA may fail to converge, even when strict complementarity ($x_1^* + x_2^* > 0$) holds. The reason for this adverse behavior is the trustregion used in PIPA, which is controlled by the norm of the infeasibility.

5 Conclusion and Outlook

The underlying theme of the preceding two sections has been to show that *small modifications* enable NLP solvers to work for MPCCs. Both SQP methods and IPM solvers either perturb or penalize the complementarity constraint. The key to proving convergence in both cases is the equivalence between strong stationarity (2.1) and the KKT conditions (2.2).

The robust solution of MPCCs as NLPs has harnessed the power of large-scale NLP solvers to this new and exciting class of problem. Despite this success, however, there still remain some open questions.

An important open question is whether global convergence results can be established and—more important—whether these results can be strengthened to provide convergence to B-stationary points [15]. For instance, it is easy to construct examples for which the NLP approaches converge to a feasible C-stationary point. Unfortunately, C-stationary points allow trivial first-order descent directions (and are really a misnomer!). Convergence to B-stationary points that are not strongly stationary can be observed in practice, even though the multiplier of the complementarity constraint ξ diverges to infinity.

Some MPCCs require global solutions to be obtained. For instance, in the context of brittle fracture identification, the global minimum corresponds to the first structural failure. Local minima are physically meaningless in this case.

Finding global minima for large NLPs is a challenging problem, and success is likely to involve the use of robust NLP techniques in conjunction with complementarity solvers.

Acknowledgements

This work was supported by the Mathematical, Information, and Computational Sciences Division subprogram of the Office of Advanced Scientific Computing Research, U.S. Department of Energy, under Contract W-31-109-Eng-38.

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The submitted manuscript has been created by the University of Chicago as Operator of Argonne National Laboratory ("Argonne") under Contract No. W-31-109-ENG-38 with the U.S. Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.